INUNDATION PATTERNS OF FARMED POTHOLE DEPRESSIONS WITH VARYING SUBSURFACE DRAINAGE

Collection

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HIGHLIGHTS

- Farmed pothole depressions in the Des Moines Lobe were observed to fill due to runoff and shallow subsurface flow.
- Six of the eight observed potholes flooded for five or more days some time during the two years of observation.
- Subsurface drainage and surface inlets reduced but did not prevent yield-limiting flooding in the observed potholes.

ABSTRACT. *The prairie pothole region (PPR) ranges from central Iowa to the northwest into Montana and south central Canada, totaling around 700,000 km^2. This area contains millions of potholes, or enclosed topographical depressions, which often inundate with rainfall. Many are located in areas that have been converted to arable agricultural land through installation of artificial drainage. However, even with drainage, potholes will pond or have saturated soil conditions during and after significant rain events. The portion of the PPR that extends into Iowa is known as the Des Moines Lobe. In this two-year study, surface water depth data were collected hourly from eight prairie potholes in the Des Moines Lobe in central Iowa to determine the surface water hydrology. These potholes included surface and subsurface drained row crops and undrained retired land, allowing for drainage comparisons. Inundation lasted five or more days at least once at six of the eight potholes, including four potholes with surface inlets and subsurface drainage, which resulted in four of fourteen growing seasons not producing a yield in part of the pothole. Water balances of four different drainage intensities showed increased infiltration due to subsurface drainage and up to 78% of outflow due to surface inlet drainage. Overall, drainage decreased the number of average inundation days, but heavy precipitation events still caused lengthy inundation periods that resulted in crop loss.*

Keywords. *Farmed wetlands, Prairie pothole, Tile drainage, Water balance.*

The prairie pothole region (PPR), which extends from central Iowa through the U.S. Upper Midwest and into Canada, was formed 12,000 years ago during the recession of the Wisconsin Glaciation (Christiansen, 1979; van der Valk, 2005). The defining feature of this region, the prairie pothole, is an enclosed depression that collects and retains water from runoff and groundwater flow (Winter and Rosenberry, 1995). As depressional wetlands, potholes are located at a local minimum elevation and have small contributing areas, which we refer to as micro-watersheds. Approximately 44% (1.38 million ha) of the Des Moines Lobe, the area of this study, drained to potholes before widespread implementation of artificial drainage (Miller et al., 2009).

In the past century, artificial drainage has been widely implemented to lower the water table in potholes and surrounding areas, which improved farm equipment access, aerated the root zone, and increased farmable acreage. While drainage started as small ditches dug by landowners, it has also been largely implemented through drainage districts that received federal funding until the 1970s (Johnson et al., 2008). Since then, wetlands have been protected by the Clean Water Act and the swampbuster provision introduced in the 1985 Food Security Act, which have curtailed new drainage of these features. However, wetlands that have been previously drained for agriculture were exempt, as long as production continued in the drained area. Overall, artificial drainage in the U.S. has impacted about 45 million ha of land now used for agriculture, with about 65% from surface drainage such as ditches and the remaining 35% from subsurface drainage (Pavelis, 1987). Throughout the Des Moines Lobe, many of the potholes have been altered due to artificial drainage, largely through subsurface drainage and surface inlets. Loss of these features due to drainage differs by state, with losses of 35% in South Dakota, 50% in North Dakota, 85% in Minnesota, and 95% to 99% in Iowa (Bishop et al., 1998; Dahl, 1990; Johnson et al., 2008). In all, about 53% of the potholes in the U.S. have been drained (Dahl, 1990). Hayashi et al. (2016) provided a robust assessment of classical prairie pot-

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hole water balances; however, they did not consider subsurface drainage, and the example potholes were in their natural state. The widespread use of subsurface drainage across the southern portion of the PPR means that water balance assessments that do not consider the role of this modification are of limited applicability to a majority of potholes in this intensively farmed and drained area.

In recent years, a few studies have been done to better understand the hydrology of drained potholes. Runoff and interflow feed potholes during rainfall events, accounting for most of the inflow water, with direct rainfall suppling only a small amount of the ponded water (Roth and Capel, 2012). Groundwater also exits the soil and becomes surface water, contributing to the ponding of potholes during some events (Amado et al., 2016). Drainage, once implemented, plays a large role in the annual water balance, removing more than half of the water in small systems such as potholes (Amado et al., 2016). In undrained potholes, the water table can be within 40 cm of the surface for more than 90% of the year (James and Fenton, 1993), while drained soils have water within 40 cm of the surface only between 0.1% and 5.6% of the time (Schilling et al., 2018). Previous research suggested that drainage removed as much as 97% of the water during pothole inundation events at one field site, while it removed no less than 78% per event at another field site (Logsdon, 2015; Roth and Capel, 2012). However, those studies did not explicitly estimate infiltration, nor did they consider partial clogging due to sediment accumulation in the tile inlet, which is why the surface inlet drainage estimates were such a large portion of the outflow. Williams et al. (2019), who evaluated the timing of subsurface and surface flow in a drained, closed depression compared to precipitation, noted that more research is needed to understand the hydrologic behavior of these features to inform appropriate conservation practices for managing impacts on downstream waters.

The hydrology of prairie potholes is also important in crop production, as much of the PPR is now used for agriculture, such as corn (*Zea mays* L.) and soybeans (*Glycine max* L.) in the Des Moines Lobe. Crops can survive a short time in anoxic conditions, and the amount of damage depends on the inundation time and plant growth stage (Lizaso and Ritchie, 1997; McDaniel et al., 2016). The duration of ponding sufficient to drown crops depends on the species and age of the vegetation. Corn drowns in about four days when it is only 30 cm tall, but it can survive for up to seven days when it is 60 cm tall (DeBoer and Ritter, 1970). The corn mortality rate after ten days of flooding is 87.8% at the V2 stage (roughly 10-day-old corn), with a decreasing mortality rate as the corn ages (Zaidi et al., 2004). Soybeans are similar in that they increase their inundation survival time as they age. Fifteen-day-old soybeans live for about three days during inundation, while 30-day-old soybeans can survive for five days (DeBoer and Ritter, 1970). The mortality and crop damage of young soybeans (V2 and V3 stages) result in reduced yield; three days of flooding caused an average reduction of 20%, and six days caused up to 93% reduction (Sullivan et al., 2001). Producers are therefore questioning the cost-benefit ratio of continuing to farm these features (e.g., Morrison, 2016). A better understanding of the frequency and extent of inundation, as well as the mechanisms of inflow and outflow, is an important part of this ongoing dialogue on management options.

The overall goal of this work is to document and assess the inundation behavior of typical closed depressions in the southern PPR. Related studies in these same depressions address water quality patterns in flooded farmed potholes (Martin et al., 2019), as well as the role of tillage practices and land cover on the frequency of inundation (Upadhyay et al., 2019). This study provides insight into the differences in pothole hydrology with differing levels of drainage, recognizing that there is a diversity of drainage circumstances for potholes in this region. The objectives of this study were to (1) compare the extent and duration of inundation at eight prairie potholes and (2) evaluate the water balances of four prairie potholes with different levels of drainage.

Methods

Site Description

Potholes were monitored at two sites for this study. One site (41.983° N, -93.688° W) is located southwest of Ames, Iowa, along the border of the Walnut and Worrell Creek HUC-12 watersheds in Story County. It contains seven of the eight monitored potholes, which were named for their unique shapes and proximity to other potholes (Lettuce, Bunny, Walnut, Gravy, Turkey, Potatoes, and Yam) (fig. 1). The second site (42.015° N, -93.743° W) is west of Ames in the Worrell Creek HUC-12 watershed in Boone County. It contains a prairie pothole (Mouth) that is part of the Conservation Reserve Program; we describe this pothole as "retired". The sites are located approximately 5.6 km (3.5 mi) apart and are both at farms operated by the Agricultural Engineering/Agronomy and Central Iowa Research Farms of Iowa State University.

Seven of the potholes (Bunny, Lettuce, Gravy, Walnut, Turkey, Potatoes, and Mouth) were sampled in 2016 and 2017. The eighth pothole (Yam) was only sampled in 2017, as it was not included until it was noted that significant flooding occurred during a heavy rainfall event in the fall of 2016. The inclusion of Yam proved important due to its tendency to flood, even in dry years such as 2017, for which it supplied over two-thirds of the total samples for the year.

The area and volume of each pothole were derived using elevation data from LiDAR at roughly 1 m resolution in the horizontal direction, which allowed better determination of the size and shape of potholes that are small in extent and shallow in depth (table 1). Previously, hydric soils such as the Okoboji soil series have been used to map potholes (NRCS, 1998). However, soil mapping limitations have led to hydric soils extending outside the elevation boundaries of some potholes, while other depressions in this study had inundation but were not mapped as hydric soils.

A majority of the land use was row crops. Areas in row crop production rotated between corn and soybeans (table 2). An access road cuts through the middle of Yam and near the edge of Gravy. Additionally, Turkey and Potatoes had miscanthus (*Miscanthus ×giganteus*) plots in their micro-watersheds during 2016, although these were returned to row crop in 2017. Yam had ponded water during planting in 2017 and

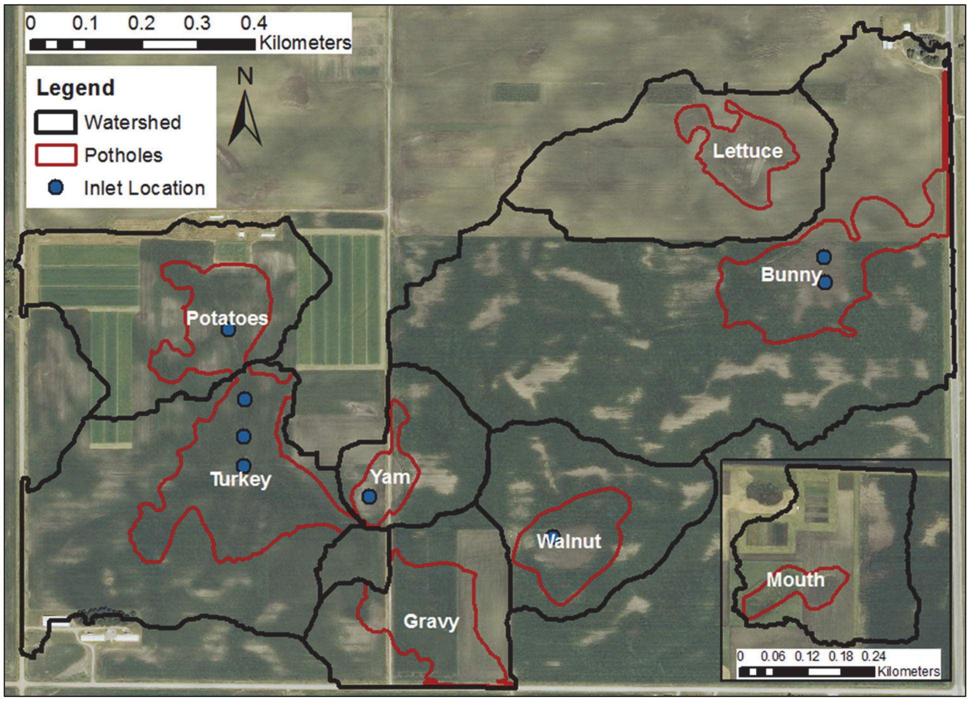


Figure 1. Pothole locations and names with micro-watershed and pothole delineation. Inset shows the second site with its retired pothole and corresponding micro-watershed.

Table 1. Summary of pothole characteristics derived using LiDAR.

Pothole	Pothole Area (ha)	Micro-Watershed Area (ha)	Bottom Elevation (m)	Overflow Elevation (m)	Maximum Volume (m^3)
Bunny	5.35	41.1	309.7	310.7	29400
Gravy	3.60	8.7	310.8	311.5	5900
Lettuce	2.11	12.7	309.6	310.4	8300
Mouth	0.94	8.4	323.6	324.0	1100
Potatoes	2.96	13.0	310.9	311.4	4100
Turkey	6.60	20.8	310.7	311.4	15400
Walnut	2.60	9.8	311.4	312.1	11800
Yam	1.20	5.4	310.9	311.7	3800

Table 2. Summary of pothole vegetation and drainage.

Pothole	Vegetation (2016-2017)	Drainage
Bunny	Soybean/corn (S/C)	Two surface inlets and subsurface drainage
Gravy	S/C	Subsurface only
Lettuce	C/S	Subsurface only
Mouth	Retired (surrounded by C/S)	No drainage (assumed)
Potatoes	S/C	Surface inlet and subsurface drainage
Turkey	S/C	Three surface inlets and subsurface drainage
Walnut	S/C	Surface inlet and subsurface drainage
Yam	S/C and grass	Surface inlet and subsurface drainage

was instead planted to grass at the end of June. Mouth was retired, with a majority of its micro-watershed in row crops and some miscanthus plots in the northern part of the micro-watershed.

The potholes had varying drainage conditions, including surface inlets and subsurface drainage (table 2). Surface inlets were documented at five of the potholes, but subsurface drainage was determined through several means. Walnut had new tile drainage installed in the fall of 2015 at an average spacing of 14 m, and shapefiles were made available by the farm manager. Lettuce had subsurface drainage installed at 15 m spacing in the spring of 2016, which was determined from Google Earth imagery (Google Earth, 2016). Subsurface drainage at Bunny had been estimated in a previous study and averaged 30 m between tile lines (Serrano, 2015). Mouth was assumed to be undrained, as it was the retired pothole. Communication with the farm manager indicated that there was subsurface drainage at Turkey, Gravy, Potatoes, and Yam, but the extent of the subsurface drainage was unknown. Most surface inlet locations were at elevations within 5 cm of the minimum elevation in the pothole, but the inlet location at Yam was 20 cm above the bottom.

WEATHER AND SOIL MOISTURE

Precipitation and soil moisture data were obtained at 15 min intervals from the Iowa Flood Information System (IFIS, 2017), which maintains a set of rain gauges at the field site near Walnut. Soil moisture was reported at depths of 5, 10, 20, and 50 cm. It was used to qualitatively inform the evaluation of antecedent moisture conditions.

Additional weather data came from USDA STEWARDS Site 702 in the North Walnut Creek basin, which was only a few kilometers southeast of the main site (USDA, 2018). The data included daily temperatures, wind speed, vapor pressure, barometric pressure, solar irradiance, and relative humidity. This information was used in determining evapotranspiration in the water balance. While precipitation was included in the STEWARDS data, the IFIS precipitation data were used because they were acquired on site, and spatial variation occurs during summer storms, which can be highly localized.

Inundation Monitoring

Each pothole was monitored for inundation depth hourly using Solinst Leveloggers placed at the bottom elevation of each pothole. The Leveloggers were positioned inside a PVC stilling well dug into the soil at each location. Data from the sensors were collected periodically to ensure that the sensors were correctly logging events, with the final data collected when the sensors were removed just before harvest. Each sensor was corrected against a centrally located Solinst Barologger to account for barometric pressure, with an additional correction made to adjust for the known sensor depth underground. Sensor installation occurred during early to mid-May of each year, while removal occurred during early to mid-October. In 2017, Yam, Mouth, and Lettuce all had early-season ponding before sensors could be installed. The ponding was noted through visual observation, but depth data were not recorded. This ponding delayed installation at Lettuce and Yam, as sensors were not installed until late May and mid-June, respectively.

Depth to Surface Area and Volume Relationships

Pond surface area and volume were determined in ArcMap 10.2 (ESRI, 2013). Surface area and volume were computed at 10 cm intervals of depth above the bottom of each pothole, and second-order equations were created to relate depth to surface area and volume. Initially, second-order equations were used from 0 m to full depth for the surface area and volume relationships, but the equations did not fit well below 0.10 m. Alternative second-order curves were created from 0.10 m to full depth, with values from 0 to 0.10 m being linear to intersect the second-order equation at 0.10 m (table 3). This worked for all potholes except Turkey, for which we interpolated values from 0 to 0.10 m and from 0.10 to 0.20 m separately before using a second-order equation at 0.20 m. Additionally, Yam was further adjusted, as GPS points taken at the site during inundation events were compared with known depths from the monitoring data and to the location and depth values on the generated map. Three days were used, and all three days showed that the mapped depths from the LiDAR DEM were 0.20 to 0.21 m deeper on average than the measured depths at those points. Due to this discrepancy, the values generated at 0.10 and 0.20 m for surface area and volume were removed, and the values for 0.30 m and higher were lowered by 0.20 m. These adjustments were made before creating the second-order equations for Yam.

Water Balance

A water balance was performed on four potholes (Bunny, Lettuce, Mouth, and Walnut), as these potholes had at least one large inundation event and were monitored for both years of the study. The water balance was described by a continuity equation in which the ponded volume was a dynamic control volume, as done by Roth and Capel (2012) (eq. 1):

$$V_t = V_{t-\Delta t} + \Delta V_t = V_{t-\Delta t} + \sum_{i=1}^{j} I_i - \sum_{m=1}^{n} O_m \qquad (1)$$

where t is the time, Δt is the time increment, V_t is the volume of ponded water at time t, $V_{t-\Delta t}$ is the volume of ponded water at time t-Δt, ΔV_t is the change in ponded water during time increment Δt, I_i is the inflow of the ith source during time increment Δt, j is the number of inflows, O_m is the outflow of the mth sink, and n is the number of outflows.

There were three potential types of inflows, as described by Roth and Capel (2012): rainfall, runoff, and interflow plus groundwater rise. Rainfall estimates were determined hourly using precipitation and the average surface area during that hour (eq. 2). Runoff and interflow/groundwater were combined into a single term, which was determined as the remainder of the water balance, as the other factors of the water balance were all estimated (eq. 3):

$$I_p = \frac{SA_t + SA_{t-\Delta t}}{2} \times P_{\Delta t} \qquad (2)$$

where I_p is the inflow from precipitation during time increment Δt (m^3), SA_t is the surface area at time t (m^2), $SA_{t-\Delta t}$ is the surface area at time t-Δt (m^2), and $P_{\Delta t}$ is the precipitation during time increment Δt (m):

$$I_{RO} + I_{IF} = \Delta V_t - I_P + \sum_{m=1}^{n} O_m \qquad (3)$$

where $I_{RO} + I_{IF}$ is the inflow from runoff and interflow during time increment Δt (m^3).

There were four potential outflows from the pothole. Three (evapotranspiration, surface inlet drainage, and infiltration) were described by Roth and Capel (2012); we added overflow as a fourth. Evapotranspiration was determined with the Penman-Monteith equation (Allen et al., 1998) using a crop coefficient of 1.05 for open water at the farmed potholes (Bunny, Lettuce, and Walnut) and 1.2 for wetland vegetation at the retired pothole (Mouth). Overflow was determined using a weir equation with a weir coefficient of 2 and a width of 1 m (eq. 4):

$$Q_w = C_w \times l \times h_t^{1.5} \qquad (4)$$

where Q_w is the outflow over the weir (m^3 h^{-1}), C_w is the weir coefficient (m$^{0.5}$ s^{-1}), l is the width of the weir (m), and h_t is the water depth above the weir (m). There is no physical weir at any of the potholes, so this is a modeling approach rather than a precise description of the physical arrangement of the pothole.

Surface inlet drainage and infiltration capacity were determined using days where interflow and runoff were assumed to have ceased; these days were then used to estimate

Table 3. Relationship of depth (*d*) to surface area and volume for each pothole from 0.1 m to full depth.

Pothole	Surface Area Equation	Volume Equation
Bunny	$25940d^2 + 37752d - 515.9$	$35202d^2 - 7361.1d + 651.1$
Gravy	$18841d^2 + 30757d - 1787.9$	$22075d^2 - 3855.9d + 247.2$
Lettuce	$20544d^2 + 20716d - 1198.1$	$17871d^2 - 3451.1d + 211.9$
Mouth	$36800d^2 + 26930d - 1912$	$20600d^2 - 3300d + 151$
Potatoes	$-8178.6d^2 + 40230d - 1121.6$	$17079d^2 - 98.143d - 88$
Turkey	$-33621d^2 + 102809d - 8936.9$	$38319d^2 - 4646d + 23.3$
Walnut	$-12568d^2 + 49183d - 699.7$	$19238d^2 + 1300.2d - 203.6$
Yam	$9114.3d^2 + 8818.6d - 685.1$	$7947.6d^2 - 1840.2d + 135.6$

the surface inlet drainage and infiltration throughout the season. To determine if interflow and runoff had ceased, daily water fluxes were determined and adjusted for direct rainfall, evapotranspiration, and overflow (eq. 5). Interflow and runoff were assumed to have ceased when the daily water flux was at or near (within 10%) the most negative value of the event (and thus the greatest water loss per surface area from the pothole). For example, during a set of storms in late September of 2016, the daily water flux was most negative for most potholes on the seventh day after storms (fig. 2):

$$F_{\Delta t} = \frac{(\Delta V_t - I_P + O_E + O_O)}{SA_{avg}} = \frac{(I_{RO} + I_{IF} - O_{SD} - O_I)}{SA_{avg}} \quad (5)$$

where $F_{\Delta t}$ is the water flux during time increment Δt (m), O_E is the outflow from evapotranspiration during time increment Δt (m^3), O_O is the outflow from overflow during time increment Δt (m^3), O_{SD} is the outflow from surface inlet drainage during time increment Δt (m^3), O_I is the outflow from infiltration during time increment Δt (m^3), and SA_{avg} is the average surface area of the ponded water during time increment Δt (m^3). In this approach, O_I includes all water that leaves the pothole by passing through the soil, so it includes infiltrated water that flows out through the drainage system.

Surface inlet drainage was determined at Bunny and Walnut. Bunny had two surface inlets with risers. The north riser had fallen over, leaving a 10 cm diameter hole for surface inlet drainage that was 3 cm above the bottom of the pothole. The inlet was assumed to behave as weir flow (eq. 4, C_w of 1.71) until ponded water was 4 cm above the inlet and as a horizontal orifice at deeper levels (eq. 6). The south riser was mangled and did not have an opening until 32 cm above the bottom of the pothole. Orifice flow was assumed for the 75 cm^2 opening. Walnut had a 20 cm diameter riser on the surface inlet. A drainage curve was determined using the manufacturer's specifications (Hickenbottom, Inc., Fairfield, Iowa), which assumed 50% blockage (eq. 7):

$$O_{SD} = C_o \times a \times \sqrt{2 \times g \times h_t} \quad (6)$$

where Q_d is the drainage flow into the surface drain (m^3 h^{-1}), C_o is the orifice coefficient (0.60), a is the area of the surface drain opening (m^2), and g is gravitational acceleration (9.81 m s^{-2}):

$$O_{SD} = -12.436 h_t^3 + 83.145 h_t^2 + 39.902 h_t \quad (7)$$

Infiltration was estimated using Darcy's law (eq. 8) for the four potholes. There was no subsurface drainage at Mouth, and it was assumed that $(D + h_{avg}) / L \approx 1$. The subsurface tile was assumed to be 1 m deep at the other three potholes. Tile spacing averaged 15 m at Lettuce, 30 m at Bunny, and 14 m at Walnut:

$$O_I = K_{sat} \times \frac{D + h_{avg}}{L} \times SA_{avg} \times \Delta t \quad (8)$$

where K_{sat} is saturated hydraulic conductivity (m per time unit), D is the depth to the subsurface tile drainage (m), h_{avg} is the average ponded water depth (m), and L is the average distance of water travel through the soil (1/3 of the average distance between tiles, m).

To have surface inlet drainage and infiltration equal the determined water flux values (fig. 2), surface inlet drainage had a drainage efficiency term added, and K_{sat} had to be estimated (eq. 9):

$$F_{\Delta t} = \frac{-d_e \times O_{SD} - O_I}{SA_{avg}} \quad (9)$$

where d_e is the drainage efficiency. These terms were adjusted until the difference between water flux and drainage was minimized using a least sum of squares. Drainage efficiency for the north inlet at Bunny was found to be 0.772, with the reduction in efficiency assumed to be caused by sediment blockage. The south riser was not found to need adjustment, and blockage was unlikely due to its protrusion into the air. The drainage efficiency at Walnut was found to be 1.16, meaning that drainage was better than the 50% blockage assumed by the manufacturer. Saturated hydraulic

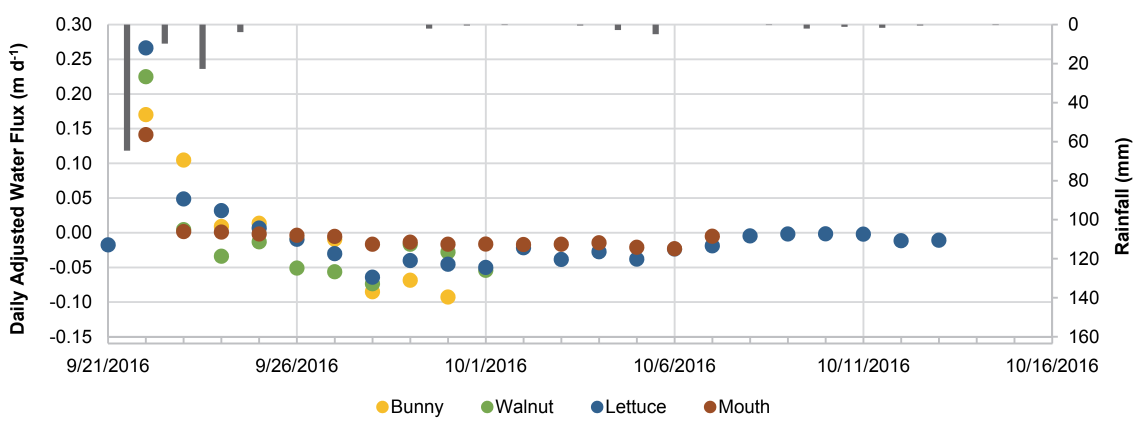


Figure 2. Daily adjusted water flux at four potholes that were part of the water balance. Fluxes were adjusted for direct rainfall, evapotranspiration, and overflow. Remaining fluxes included inflows from runoff and infiltration, and outflows from surface inlet drainage and infiltration. When fluxes were at or near (±10%) the most negative value, runoff and interflow were assumed to have ceased, leaving only surface inlet drainage and infiltration. In this example, runoff and interflow stopped on 9 September 2016, which was the seventh day of the event.

conductivity varied between potholes: 0.130 m d^{-1} (Bunny), 0.024 to 0.364 m d^{-1} varying linearly with maximum depth (Lettuce), 0.017 m d^{-1} (Mouth), and 0.160 m d^{-1} (Walnut).

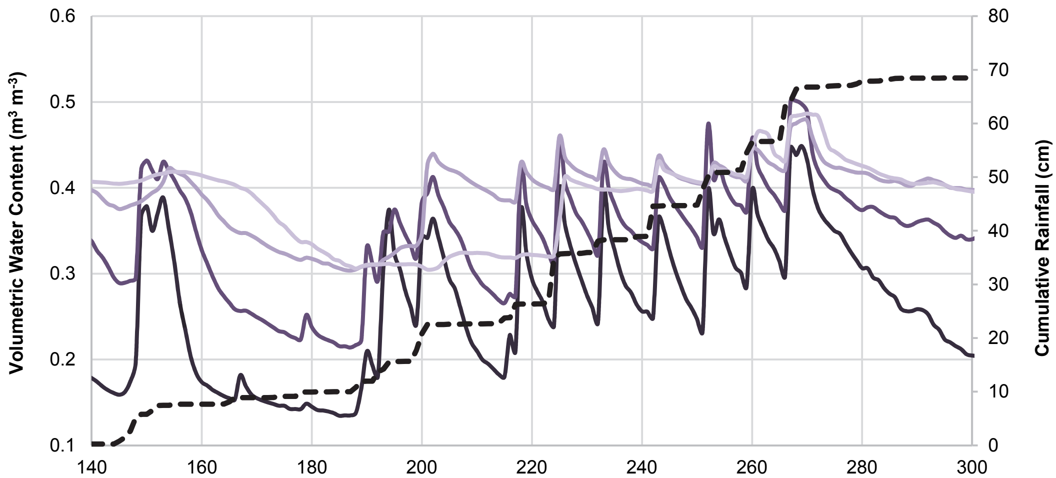
Water Balance Comparison

The water balance from this study was compared to the water balances reported by Roth and Capel (2012) and Logsdon (2015). In Roth and Capel (2012) and Logsdon (2015), surface inlet drainage was estimated using maximum orifice flow, regardless of flow reduction due to risers or partial clogging, as considered in this study. In addition, those studies did not directly estimate infiltration but instead used negative values of the remainder term, which did not occur in every event.

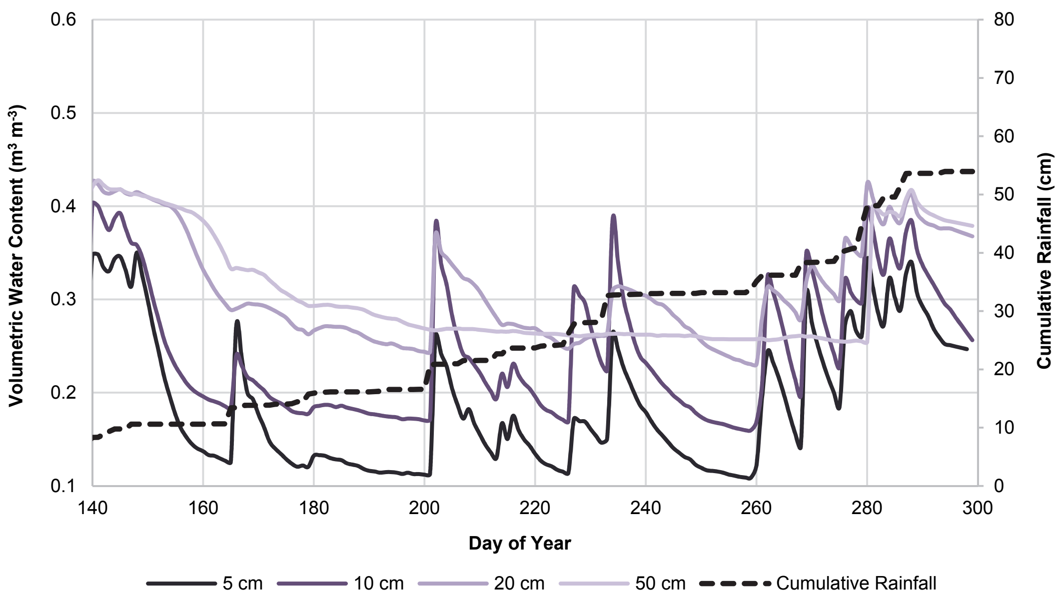
Results and Discussion

Rainfall

Total rainfall depths during the 2016 and 2017 monitoring seasons were 68 cm (27 in.) and 54 cm (21 in.), respectively, and were about 10% above and 10% below the 30-year average of 61 cm (fig. 3). Both 2016 and 2017 had near-average precipitation during April and May before being uncharacteristically dry during June (days 151 to 181). In 2016, June received only about one-fifth of the normal precipitation, which resulted in low soil moisture at 50 cm that persisted until August (fig. 3). There was average precipitation in July (days 183 to 213) and nearly double the average precipitation in August (days 214 to 244) and September (days 245 to 274). However, in 2017, precipitation remained at or below average throughout the growing season and did not see a major monthly excess until October (days 275 to 300),



(a) 2016



(b) 2017

Figure 3. Cumulative rainfall and soil volumetric water content for (a) 2016 and (b) 2017 from mid-May through late October. Rainfall was higher in 2016 than 2017, which led to higher water content in the soil and more ponding events.

resulting in low soil moisture through the growing season. Rainfall intensity also varied between years, with five events greater than 20 mm h^{-1} in 2016 and a maximum of 16.9 mm h^{-1} in 2017.

Inundation Events

A total of 42 inundation events occurred among the eight potholes, for a total of 200 days of ponding. This was without any inundation data for Yam in 2016, which is significant because Yam was inundated for 48 days in 2017, the drier year (table 4). In comparison, Mouth and Lettuce were inundated for 11 days and one day, respectively, in 2017 and for 35 and 55 days in 2016. Six potholes had at least one event that lasted four or more days (fig. 4). Mouth had five events of that length, while Yam had four in 2017 alone. Lettuce also had four events of that length, while no other pothole had more than one event of that length. Most of the events (24 of the 42 events) were of two days or less.

There were 15 inundation events between May and August of 2016, but none lasted longer than six days or had a peak depth above 20 cm (fig. 5). One event at Lettuce had six straight days of ponding or saturated soil that led to a portion of the crop drowning shortly after planting, but none of the other events had large areas of crop drowning. The largest precipitation event during the two-year monitoring period occurred in mid-August of 2016 and totaled nearly 80 mm (3.1 in.), but large cracks had opened up in the potholes by that time due to a lack of rain. The low soil moisture at 50 cm (fig. 3) rose sharply during this event, which is likely the reason for little to no inundation at the potholes.

The largest inundation event at each pothole (by time and depth) occurred in September 2016. A series of storms caused precipitation events of 5.3, 5.2, 6.4, and 2.2 cm to occur within a 17-day period. Inundation at Lettuce lasted from the first event on September 8 until October 14, totaling 37 days and having a peak inundation depth of 58.6 cm. Mouth was inundated for five days after each of the first two storms, while the third and fourth storms caused 17 days of consecutive ponding that had a peak depth of 32.6 cm. This caused overflow at Mouth, which had an overflow point of 31.4 cm. Despite having surface inlets, Bunny and Walnut also saw significant inundation that lasted more than a week after 6.4 cm of rainfall, with peak depths of 44.8 and 34.3 cm, respectively. During this series of storms, inundation at Gravy, Potatoes, and Turkey totaled 2, 4, and 6 days, respectively. While Yam was not monitored in 2016, inundation from these storms lasted through harvest time, and the crop was not harvested.

There was less inundation in 2017, as it was a drier year than 2016. Inundation occurred at Yam, Walnut, Lettuce, and Mouth during the middle of May, and this inundation prevented planting at Yam and in part of Walnut. From June onward, Yam was the only pothole to have inundation. A lack of rainfall resulted in low soil moisture through the summer of 2017 that lasted into October. A series of seven rainfall events with 1 to 4 cm of rainfall occurred during a 20-day period from late September until mid-October. This resulted in shallow but sustained ponding at Yam that peaked at 20.6 cm, although no other pothole had inundation.

Inundation per pothole varied, with inundation occurring for an average of 7.8% of the monitored days (table 4). There was inundation for an average of 11.0% of the 173 monitored days in 2016, which was the wetter of the two years. Lettuce and Mouth accounted for a majority of the inunda-

Table 4. Numbers and percentages of days with inundation during the monitoring period at the eight potholes.

Year		Bunny	Gravy	Lettuce	Mouth	Potatoes	Turkey	Walnut	Yam	Total
2016	Number of inundated days	13	5	55	35	4	6	15	N/A	133
	Number of days monitored	173	173	173	173	173	173	173	N/A	1211
	Days with inundation (%)	7.5	2.9	31.8	20.2	2.3	3.5	8.7	N/A	11.0
2017	Number of inundated days	2	0	1	11	0	2	3	48	67
	Number of days monitored	171	171	171	171	171	171	171	171	1368
	Days with inundation (%)	1.2	0.0	0.6	6.4	0.0	1.2	1.8	28.1	4.9
Total	Number of inundated days	15	5	56	46	4	8	18	48	200
	Number of days monitored	344	344	344	344	344	344	344	171	2579
	Days with inundation (%)	4.4	1.5	16.3	13.4	1.2	2.3	5.2	28.1	7.8

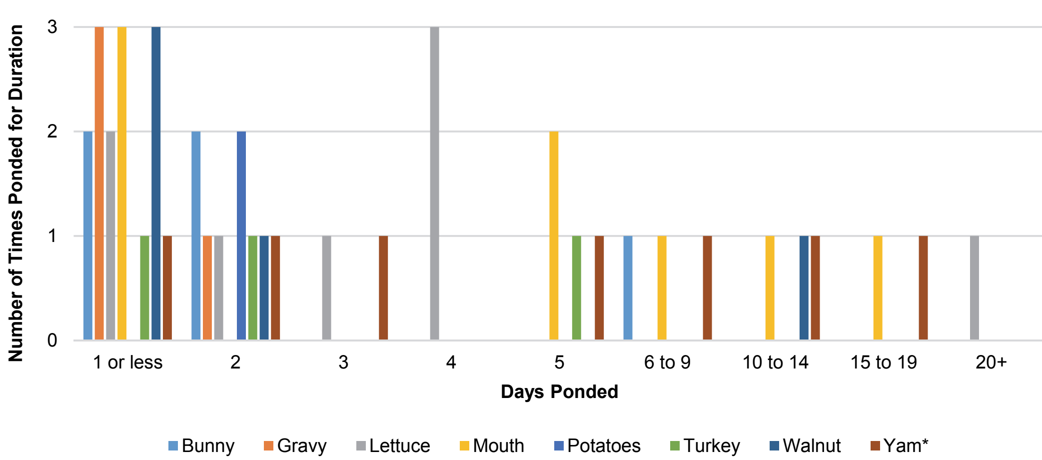
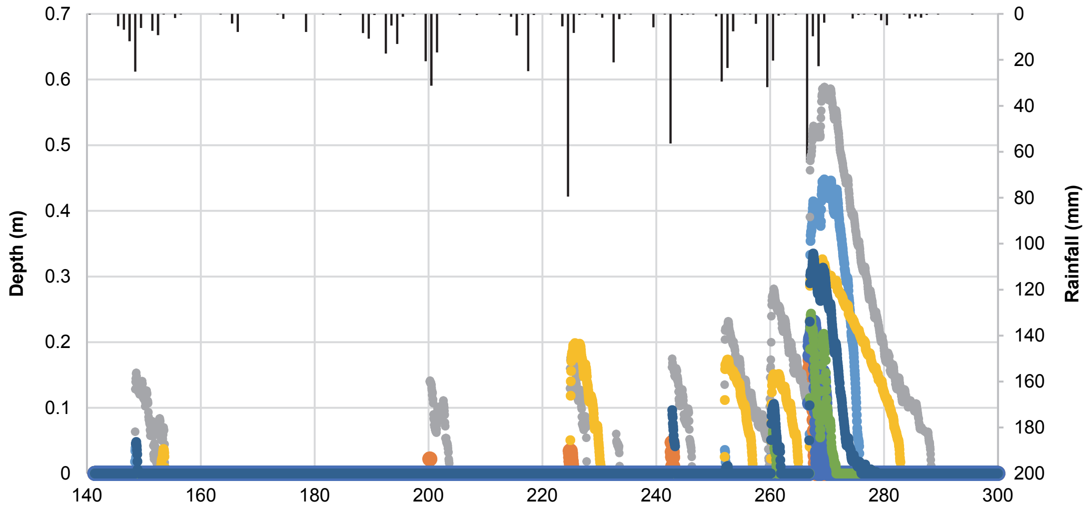
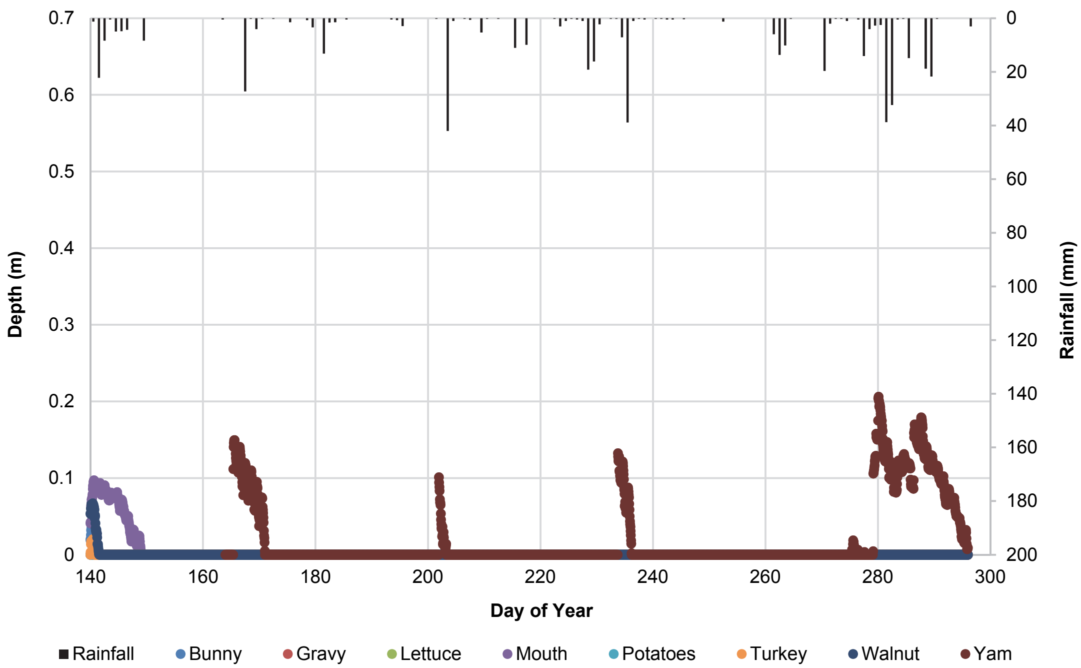


Figure 4. Duration of inundation events and number of events at each pothole (*Yam data are for 2017 only).



(a) 2016



(b) 2017

Figure 5. Water depth and daily rainfall at eight potholes for (a) 2016 and (b) 2017 from mid-May through late October.

tion in 2016, with 55 and 35 days, respectively, of the 133 total inundation days. The other potholes in 2016 had inundation between 2.3% (Potatoes) and 8.7% (Walnut) of the days. In 2017, there was inundation for an average of 4.9% of the 171 monitored days, even with the addition of Yam, which accounted for 48 (72%) of the 67 inundated days. Inundation at the other potholes varied from no inundation (Gravy and Potatoes) to 6.4% of the monitored days (Mouth) in 2017.

The differences in inundation time can largely be attributed to differences in drainage. Mouth, the retired pothole with no drainage, had inundation for 13.4% of the monitored days. Lettuce, the only farmed pothole without a surface inlet, was inundated for 16.3% of the monitored days. Yam, which had a surface inlet that was 20 cm above the bottom elevation, was inundated for 28.1% of the 2017 monitoring period, with most of its inundated days having less than 20 cm of maximum depth. The other five potholes all had surface inlets within 5 cm of the bottom elevation, and inundation at these potholes ranged between 1.2% and 5.2% of the monitored days, with an average of 2.9%. The results from these five potholes closely match the results of a groundwater study of eight drained potholes by Schilling et al. (2018), in which the water table was above the surface

1.5% of the time and ranged from >0.5% to 4.0% at individual potholes.

No crops were harvested from an individual pothole in four (29%) of the 14 growing seasons, which included one crop drowned out, one crop inundated during harvesting, and inability to plant due to wet conditions at two potholes. This is lower than the 40% reported by Schilling et al. (2018). However, conditions during this study also tended to be drier than average during June and July, which is when the crops are younger and more susceptible to drowning (DeBoer and Ritter, 1970; Zaidi et al., 2004). The largest inundation event occurred in the fall of 2016, after the grain had grown. Harvest was delayed until the field dried, and the grown crop was lost only at Yam. However, inundation during this event lasted between 2 and 37 days at the farmed potholes, and crops would have been more severely impacted had the event occurred earlier in the season when the crops were growing. Additionally, we did not attempt to estimate the depressed yields for these potholes, but rather tracked only the total crop loss. For comparison, V2 stage corn (roughly 10 days old) has a mortality rate of 87.8% with ten days of inundation (Zaidi et al., 2004), while V2 stage soybeans have a 93% reduction in yield with just six days of inundation (Sullivan et al., 2001).

WATER BALANCE

Water balance estimates were calculated on an hourly basis. However, some internalized errors occurred due to the methods used, which require acknowledgement. First, all of the drainage outflows were estimated, and any remainder to the water balance was attributed to the combined runoff and interflow term. Due to surface inlet drainage and infiltration being determined through least sum of squares on days when runoff and interflow were assumed to have ceased, there was a remainder on those days that could be positive or negative and that was still associated with the runoff and interflow term (as it was the only remainder term). Remainders were low in comparison to days when runoff and interflow were present, and the sum of the positive and negative values resulted in the totals between -15 m^3 (Mouth) and 32 m^3 (Bunny), which changed the runoff and interflow estimates by less than 1%. The second internalized error was a small diurnal variance that we observed in the water depth data. Again, this was captured in the runoff and interflow remainder term. This variance did not affect final estimates and simply caused some hours of the day to have increased runoff and interflow, while other hours had decreased inflow.

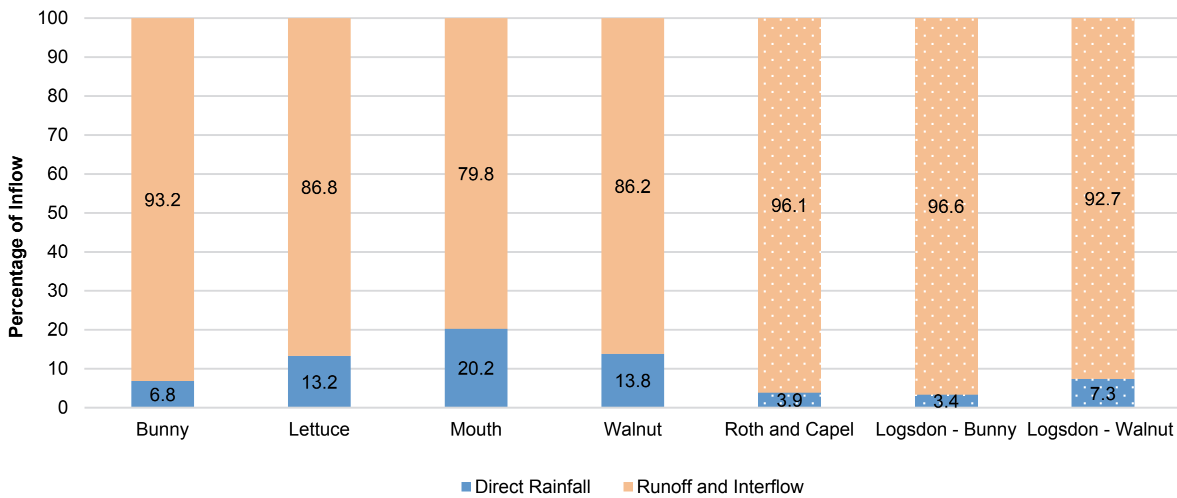
Total inflows varied among the potholes (table 5 and fig. 6). Lettuce was inundated the most, covering the largest surface area, which led to the greatest amount of direct rainfall. Runoff and interflow were largest at Bunny by both the total amount and the percentage of inflow. Micro-watershed area and drainage were the likely causes for runoff and interflow being a larger percentage of the inflow at Bunny, Lettuce, and Walnut compared to Mouth. The micro-watershed area at Bunny was three to five times larger than at the other potholes, which created the potential for greater runoff and interflow and also delayed the peak in both the hourly and daily inflows at Bunny (table 6), although interflow lasted six days at each pothole. The micro-watershed areas at Lettuce, Mouth, and Walnut were similar (8.4 to 12.7 ha), and drainage was the likely cause of the inflow differences. Drainage lowered the water levels in the potholes at a faster rate than natural infiltration, which caused a greater difference in the water potential between the pothole and its micro-watershed than without drainage. This greater potential difference would cause additional interflow to enter the pothole, as described by Darcy's law.

Outflows had large differences between potholes and were largely influenced by drainage. Bunny had the most surface inlet drainage, which was estimated to be 78% of the total. The 10 cm diameter north inlet with no riser had 55% of the total outflow (6856 m^3), while the south inlet with a riser accounted for 23% (2773 m^3). Walnut had only one surface inlet, which resulted in 37% of the total outflow. Walnut also had more significant subsurface drainage than Bunny, which increased its infiltration ability. Lettuce had no surface inlet drainage, but subsurface drainage increased the infiltration compared to Mouth. The percentage of outflow due to evapotranspiration was largest at Mouth, which was largely due to slower infiltration rather than the adjustment factor used in the Penman-Monteith equation. The infiltration (77%) and evapotranspiration (19.3%) at Mouth closely matched the percentages found for a wetland in Saskatchewan, where infiltration accounted for 75% and evapotranspiration accounted for 25% (Hayashi et al., 1998). Mouth was also the only pothole to overflow, which was due to its shallow maximum depth (0.31 m).

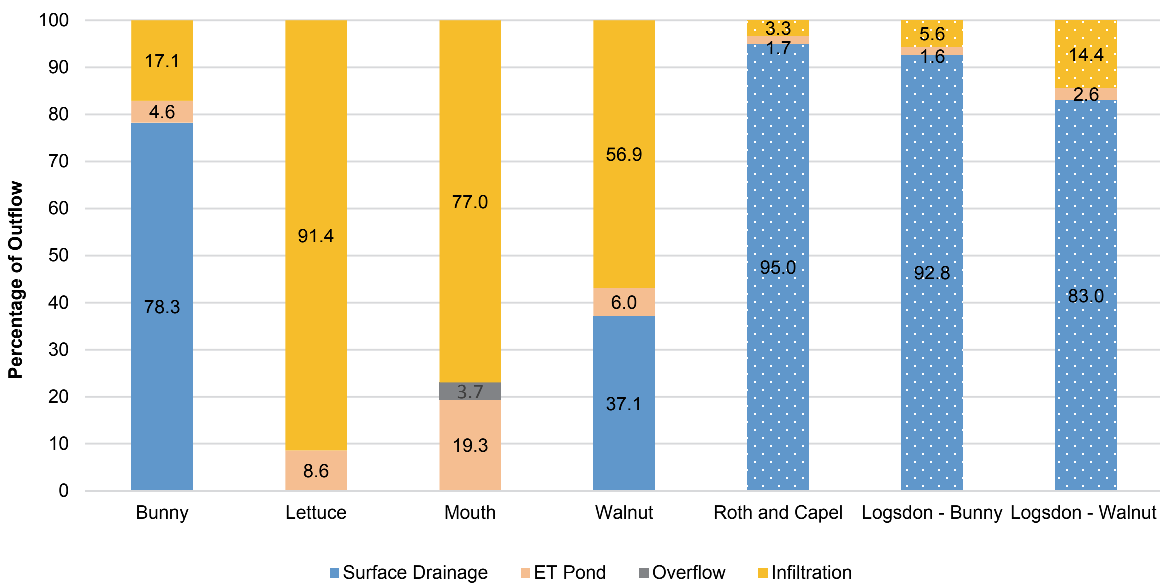
Surface inlet drainage and infiltration from the three farmed potholes (Bunny, Lettuce, and Walnut) exited through the tile drainage and entered nearby streams. In their natural state, potholes contribute to streams only during overflow or slowly as groundwater, but tile drainage removes surface water from potholes more quickly. During the monitoring period, 3% to 7% of the rainfall on the micro-watersheds became surface water in the potholes, with over 90% of the surface water draining through artificial drainage. During the largest ponding event (September 2016), 36% to 61% of the rainfall on the micro-watersheds became surface water. Groundwater was also removed from the mi-

Table 5. Inflow and outflow totals for the study period. Totals from Roth and Capel (2012) and Logsdon (2015) are included for comparison.

Pothole	Direct Rainfall (m^3)	Runoff and Interflow (m^3)	Surface Inlet Drainage (m^3)	ET Pond (m^3)	Overflow (m^3)	Infiltration (m^3)
Bunny	841	11,599	9737	578	0	2126
Lettuce	1425	9343	0	921	0	9847
Mouth	580	2287	0	555	105	2208
Walnut	714	4469	1922	312	0	2949
Roth and Capel (2012)	703	17,380	17,163	311	0	593
Logsdon (2015) - Bunny	4549	127,928	122,277	2123	0	7414
Logsdon (2015) - Walnut	2757	34,892	33,869	1046	0	5878



(a) Inflows



(b) Outflows

Figure 6. (a) Inflows and (b) outflows as a percentage of the total. Percentages of the totals from Roth and Capel (2012) and Logsdon (2015) are included for comparison.

Table 6. Hourly and daily runoff and interflow estimates (m^3) at four potholes that were part of the water balance during September 22-27, 2016. At Bunny, the maximum hourly values were delayed by an hour, and the maximum daily values were delayed by a day. These delays are attributed to the larger micro-watershed area at Bunny.

	Date	Hour	Bunny	Lettuce	Mouth	Walnut
Hourly	22 Sept.	20	116	95	0	44
	22 Sept.	21	18	134	10	57
	22 Sept.	22	184	1072	418	864
	22 Sept.	23	1052	851	390	680
	23 Sept.	0	702	225	78	196
	23 Sept.	1	408	101	42	83
Daily	22 Sept.	-	1370	2170	818	1644
	23 Sept.	-	3138	1566	168	1038
	24 Sept.	-	1738	1468	162	428
	25 Sept.	-	2094	1375	150	763
	26 Sept.	-	1586	1042	120	189
	27 Sept.	-	1491	561	101	46

cro-watersheds through artificial drainage, meaning that more than 3% to 7% of the rainfall was removed during the monitoring period. Timing also varied between potholes, with Bunny (two surface inlets) draining 11,528 m^3 (36% of the rainfall on the micro-watershed) in ten days during the largest ponding event, while Lettuce (no surface inlets but greater subsurface drainage density) drained 9473 m^3 (61%) in 24 days. Overall, outflows to streams from the potholes were variable, with differing frequencies and lengths of ponding depending on the artificial drainage implemented, and these differences in artificial drainage mean that future modeling cannot assume uniformity of potholes on a watershed scale.

Previous studies by Roth and Capel (2012) and Logsdon (2015) produced water balances that were heavily defined by the assumption of full flow for the surface inlet, with outflow from surface inlet drainage being between 83% and 95% of the total. Outflows for individual events often had no infiltration, with study totals of 3.3% to 14.4%, and the maximum evapotranspiration at a pothole was only 2.6% of the total outflow. In contrast, our study estimated infiltration due to subsurface drainage and did not assume full flow for surface inlets. For the two water balances with surface inlets, Bunny and Walnut had 78% and 37%, respectively, of their outflow due to surface inlet drainage, while infiltration was estimated at 17% and 57%, respectively. Evaporation was 4.6% (Bunny) and 6.0% (Walnut) of the total outflow. Total inflow was also impacted by the change in methods, as interflow was used to balance the surface inlet drainage when water levels were not dropping. Because this study had less estimated drainage, the interflow estimates were lower.

Comparisons to the potholes in the study by Logsdon (2015) are important, as they show the differences that can result from applying differing assumptions. The Logsdon potholes were at the same site as this study, with Bunny (north depression) and Walnut (south depression) being the same potholes. Inflows and outflows were expected to be higher in 2010 due to higher precipitation (108 cm from April to October) compared to our study (68 cm in 2016 and 54 cm in 2017), but the percentages would be expected to be similar. Logsdon (2015) noted the potential for water backup and partial clogging of the tiles. While our study did not address potential water backup, an effort was made to determine partial clogging through use of the drainage efficiency coefficient. The inclusion of this coefficient showed that the previous water balances by Roth and Capel (2012) and Logsdon (2015) likely overestimated surface inlet drainage, which resulted in overestimation of runoff and interflow and underestimation of infiltration.

Conclusions

This study compared the extent and duration of inundation at eight prairie potholes and evaluated the water balances of four potholes with different levels of drainage. Eight potholes on the Des Moines Lobe in central Iowa were studied for two years, and inundation lengths and frequencies were compared. Additionally, four potholes were part of a water balance, which estimated inflows (direct rainfall, runoff, and interflow) and outflows (evapotranspiration, overflow, infiltration, and surface inlet drainage) using an adaptation of the methods used by Roth and Capel (2012). While surface inlet drainage decreased the ponding length and frequency, crop drowning due to inundation was still present. Inundation lasted for five or more days at least once at six of the eight potholes, including four potholes with surface and subsurface drainage. Inundation and saturated soils resulted in four of the 14 (29%) crops not producing a yield in part of a pothole, despite low precipitation during June and July of each year, when the crops were younger and more susceptible to drowning (DeBoer and Ritter, 1970; Zaidi et al., 2004). For the water balances, the surface inlet drainage accounted for partial clogging, and infiltration estimates were determined using subsurface drainage. The outflows were estimated simultaneously in this study, which resulted in increased infiltration estimates, reduced outflow due to surface inlet drainage, and reduced inflow from runoff and interflow compared to the studies by Roth and Capel (2012) and Logsdon (2015). Overall, drainage decreased the average number of inundated days but did not fully prevent drowning of crops during dry growing seasons. In addition, the inclusion of infiltration estimates and partial clogging of the surface inlet drainage showed that previous water balances of potholes likely overestimated surface inlet drainage, runoff, and interflow while underestimating infiltration.

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